

## WEAK LENSING CONSTRAINTS ON GALAXY HALOS

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**Abstract.** Weak gravitational lensing has become an important tool to study the properties of dark matter halos around galaxies, thanks to the advent of large panoramic cameras on 4m class telescopes. This area of research has been developing rapidly in the past few years, and in these proceedings we present some results based on the Red-Sequence Cluster Survey, thus highlighting what can be achieved with current data sets. We present results on the measurement of virial masses as a function of luminosity and the extent of dark matter halos. Much larger surveys are underway or planned, which will result in an impressive improvement in the accuracy of the measurements. However, the interpretation of future results will rely more and more on comparison with numerical simulations, thus providing direct tests of galaxy formation models.

### 1 Introduction

Observations of the dynamics of stars and gas in galaxies have provided important evidence for the existence of dark matter halos around galaxies. These studies have also shown that tight relations exist between the baryonic and dark matter components. The latter findings provide important constraints for models of galaxy formation, as their origin needs to be explained.

However, dynamical methods require visible tracers, which typically can be observed only in the central regions of galaxies, where baryons are dynamically important. In this regime, the accuracy of simulations is limited and the physics complicated. Hence the interpretation of observations is complicated and one needs to proceed cautiously. In addition assumptions about the orbit structure need to be made. Instead, it would be more convenient to have observational constraints on quantities that are robust (both observationally and theoretically) and easily extracted from numerical simulations. An obvious quantity of interest is the virial mass of the galaxy.

Fortunately, in recent years it has become possible to probe the outer regions of galaxy dark matter halos, either through the dynamics of satellite galaxies (e.g.,

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Prada et al. 2003) or weak gravitational lensing. In these proceedings we focus on the latter approach, which uses the fact that the tidal gravitational field of the dark matter halo introduces small coherent distortions in the images of distant background galaxies. This signal can nowadays be easily detected in data from large imaging surveys. It is important to note, however, that weak lensing cannot be used to study individual galaxies, but ensemble averaged properties instead.

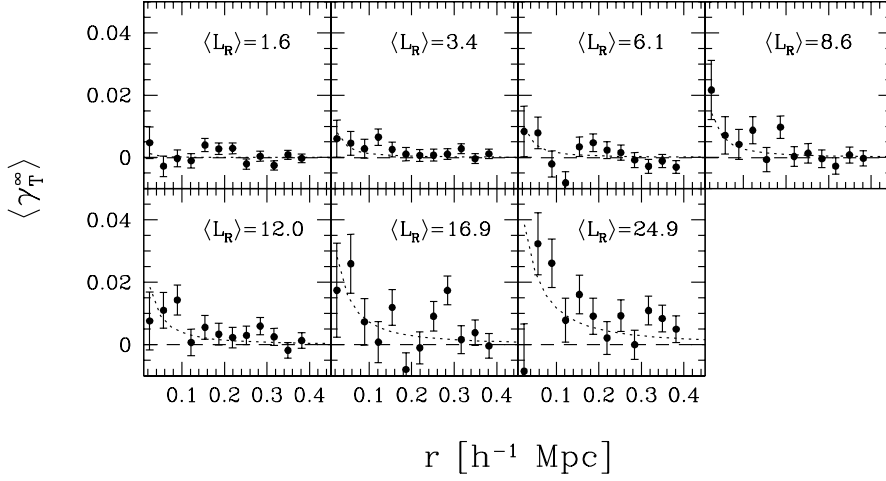
Since the first detection of this so-called galaxy-galaxy lensing signal by Brainerd et al. (1996), the significance of the measurements has improved dramatically, thanks to new wide field CCD cameras on a number of mostly 4m class telescopes. This has allowed various groups to image large areas of the sky, yielding the large numbers of lenses and sources needed to measure the lensing signal. Results from the Sloan Digital Sky Survey (SDSS) provided a major improvement (e.g., Fisher et al. 2000; McKay et al. 2001) over early studies. Apart from the increased surveyed area, an important advantage of the more recent SDSS studies (McKay et al. 2001; Guzik & Seljak 2002) is the availability of (photometric) redshift information for the lenses and sources. This has enabled studies of the dark matter properties as a function of baryonic content.

Here, we highlight recent progress by presenting results from the Red-Sequence Cluster Survey (RCS; Gladders & Yee 2005). Recently Hsieh et al. (2005) derived photometric redshifts for a subset of the RCS and we use these results to study the virial mass as a function of luminosity. We also present measurements of the extent of dark matter halos and discuss measurements of their shapes. We conclude by discussing what to expect in the near future, when much larger surveys start producing results.

## 2 Virial masses

One of the major advantages of weak gravitational lensing over most dynamical methods is that the lensing signal can be measured out to large projected distances from the lens. However, at large radii, the contribution from a particular galaxy may be small compared to its surroundings: a simple interpretation of the measurements can only be made for ‘isolated’ galaxies. What one actually observes, is the galaxy-mass cross-correlation function. This can be compared directly to models of galaxy formation (e.g., Tasitsiomi et al. 2004). Alternatively, one can attempt to select only isolated galaxies or one can deconvolve the cross-correlation function, while making some simplifying assumptions. In this section we discuss results for ‘isolated’ galaxies, whereas in the next section, which deals with the extent of dark matter halos, we use the deconvolution method.

A detailed discussion of the results presented in this section can be found in Hoekstra et al. (2005). The measurements presented here are based on a subset of the RCS for which photometric redshifts were determined using  $B, V, R_C, z'$  photometry (Hsieh et al. 2005). We selected galaxies with redshifts  $0.2 < z < 0.4$  and  $18 < R_C < 24$ , resulting in a sample of  $\sim 1.4 \times 10^5$  lenses. However, to simplify the interpretation of the results, we proceed by selecting ‘isolated’ lenses. To do so, we only consider lenses that are at least 30 arcseconds away from a brighter

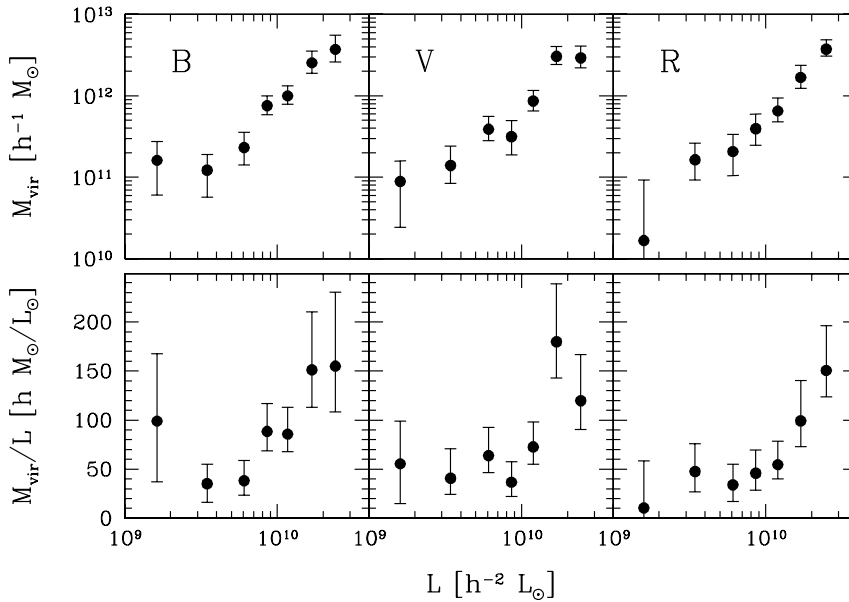


**Fig. 1.** Tangential shear as a function of projected (physical) distance from the lens for each of the seven restframe  $R$ -band luminosity bins. To account for the fact that the lenses have a range in redshifts, the signal is scaled such that it corresponds to that of a lens at the average lens redshift ( $z \sim 0.32$ ) and a source redshift of infinity. The mean restframe  $R$ -band luminosity for each bin is also shown in the figure in units of  $10^9 h^{-2} L_{R\odot}$ . The strength of the lensing signal clearly increases with increasing luminosity of the lens. The dotted line indicates the best fit NFW model to the data.

galaxy (see Hoekstra et al., 2005 for details). Note, that bright galaxies are not necessarily isolated. For such galaxies, however, we expect the lensing signal to be dominated by the galaxy itself, and not its fainter companions.

We split the sample into 7 luminosity bins and measure the mean tangential distortion out to 2 arcminutes from the lens. The resulting tangential shear profiles are shown in Figure 1 for the bins of increasing rest-frame  $R$  luminosity. The results for the  $B$  and  $V$  band are very similar. We estimate the virial mass for each bin by fitting a NFW (Navarro, Frenk & White 1996) profile to the signal. The resulting virial mass as a function of rest-frame luminosity is presented in Figure 2. These findings suggest a power-law relation between the mass and the luminosity, although this assumption might not hold at the low luminosity end. We fit a power-law model to the measurements and find that the slope is  $\sim 1.5 \pm 0.2$  for all three filters. This result is in good agreement with results from the SDSS (Guzik & Seljak, 2002) and predictions from models of galaxy formation (Yang et al. 2003). As stressed by Guzik & Seljak (2002), the observed slope implies that rotation curves must decline substantially from the optical to the virial radius.

For a galaxy with a luminosity of  $10^{10} h^{-2} L_{B\odot}$  we obtain a virial mass of  $M_{\text{vir}} = 9.9^{+1.5}_{-1.3} \times 10^{11} h^{-1} M_{\odot}$ . We note that if the mass-luminosity relation has an intrinsic scatter, our mass estimates are biased low (Tasitsiomi et al. 2004). The amplitude of this bias depends on the assumed intrinsic scatter. The results



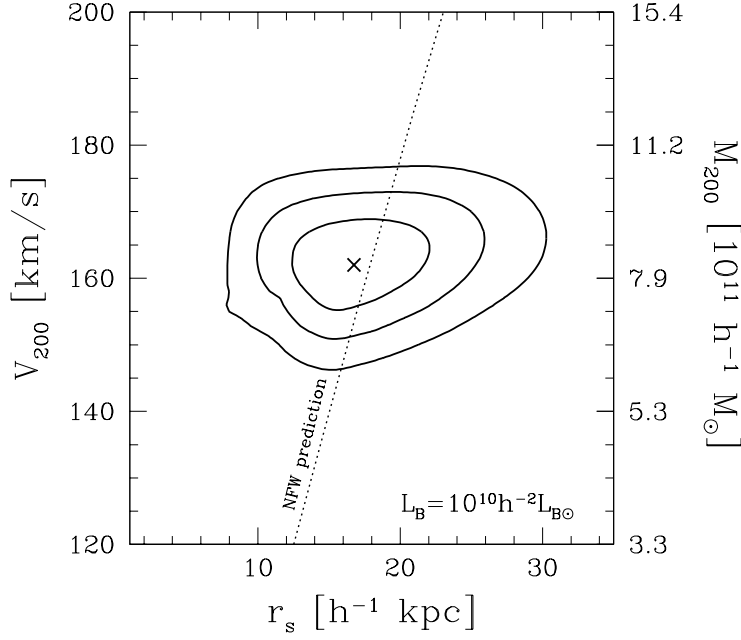
**Fig. 2.** *upper panels:* Virial mass as a function of the rest-frame luminosity in the indicated filter. The dashed line indicates the best fit power-law model for the mass-luminosity relation, with a power slope of  $\sim 1.5$ . *lower panels:* Observed rest-frame virial mass-to-light ratios. The results suggest a rise in the mass-to-light ratio with increasing luminosity, albeit with low significance.

presented in Tasitsiomi et al. (2004), however, do indicate that the slope of the mass-luminosity relation is not affected.

### 3 Extent and shapes of halos

The galaxy-mass cross-correlation function is the convolution of the galaxy distribution and the underlying galaxy dark matter profiles. Provided we have a model for the latter, we can ‘predict’ the expected lensing signal. Such an approach naturally accounts for the presence of neighbouring galaxies. It essentially allows us to deconvolve the galaxy-mass cross-correlation function, under the assumption that all clustered matter is associated with the lenses. If the matter in galaxy groups (or clusters) is associated with the halos of the group members (i.e., the halos are indistinguishable from the halos of isolated galaxies) our results should give a fair estimate of the extent of galaxy halos. However, if a significant fraction of the dark matter is distributed in common halos, a simple interpretation of the results becomes more difficult.

We use such a maximum likelihood approach to place constraints on the properties of dark matter halos. A detailed discussion of the results can be found in Hoekstra et al. (2004). The analysis presented here uses only  $R_C$  imaging data



**Fig. 3.** Joint constraints on  $V_{200}$  and scale radius  $r_s$  for a fiducial galaxy with  $L_B = 10^{10} h^{-2} L_{B\odot}$ , with an NFW profile. The corresponding values for  $M_{200}$  are indicated on the right axis. The contours indicate the 68.3%, 95.4%, and the 99.7% confidence on two parameters jointly. The cross indicates the best fit value. The dotted line indicates the predictions from the numerical simulations, which are in excellent agreement with our results.

from the RCS, and therefore lacks redshift information for the individual lenses. Nevertheless, these measurements allow us to place tight constraints on the extent and masses of dark matter halos.

In our maximum likelihood analysis we consider  $r_s$  and  $V_{200}$  (or equivalently the mass  $M_{200}$ ) as free parameters. Figure 3 shows the joint constraints on  $V_{200}$  and scale radius  $r_s$  for a fiducial galaxy with  $L_B = 10^{10} h^{-2} L_{B\odot}$ , when we use an NFW profile for the galaxy dark matter profile. Numerical simulations of CDM, however, show that the parameters in the NFW model are correlated, albeit with some scatter. Hence, the simulations make a definite prediction for the value of  $V_{200}$  as a function of  $r_s$ . The dotted line in Figure 3 indicates this prediction. If the simulations provide a good description of dark matter halos, the dotted line should intersect our confidence region, which it does.

This result provides important support for the CDM paradigm, as it predicts the correct “size” of dark matter halos. It is important to note that this analysis is a direct test of CDM (albeit not conclusive), because the weak lensing results are inferred from the gravitational potential at large distances from the galaxy center, where dark matter dominates. Most other attempts to test CDM are confined to the inner regions, where baryons are, or might be, important.

Another prediction from CDM simulations is that halos are not spherical but triaxial instead. We note, however, it is not completely clear how the interplay with baryons might change this. For instance, Kazantzidis et al. (2004) find that simulations with gas cooling are significantly rounder than halos formed in adiabatic simulations, an effect that is found to persist almost out to the virial radius. Hence, a measurement of the average shape of dark matter halos is important, because both observational and theoretical constraints are limited. Weak gravitational lensing is potentially one of the most powerful way to derive constraints on the shapes of dark matter halos. The amount of data required for such a measurement, however, is very large: the galaxy lensing signal itself is tiny, and now one needs to measure an even smaller azimuthal variation. We also have to make assumptions about the alignment between the galaxy and the surrounding halo. An imperfect alignment between light and halo will reduce the amplitude of the azimuthal variation detectable in the weak lensing analysis. Hence, weak lensing formally provides a lower limit to the average halo ellipticity.

Hoekstra et al. (2004) attempted such a measurement, again using a maximum likelihood model. They adopted a simple approach, and assumed that the (projected) ellipticity of the dark matter halo is proportional to the shape of the galaxy:  $e_{\text{halo}} = f e_{\text{lens}}$ . This yielded a best fit value of  $f = 0.77^{+0.18}_{-0.21}$  (68% confidence), suggesting that, on average, the dark matter distribution is rounder than the light distribution. Note, however, that even with a data set such as the RCS, the detection is marginal. A similar, quick analysis of imaging data from the CFHTLS and VIRMOS-Descart surveys give lower values for  $f$ , suggesting that the RCS result is on the high side.

Recently, an independent weak lensing measurement of halo shapes was reported by Mandelbaum et al. (2005), based on SDSS observations. For the full sample of lenses they do not detect an azimuthal variation of the signal, which is somewhat at odds with the Hoekstra et al. (2004) findings. However, as Mandelbaum et al. (2005) argue, the comparison is difficult at best, because of different sensitivity to lens populations, etc. and differences in the analyses. However, the approach used by Mandelbaum et al. (2005) has the nice feature that it is more ‘direct’, compared to the maximum likelihood approach. The latter ‘always gives an answer’, but in our case it is difficult to determine what scales or galaxies contribute most to the signal. Interestingly, Mandelbaum et al. (2005) also split the sample into blue (spiral) and red (elliptical) galaxies. The results suggest a positive alignment between the dark matter halo and the brightest sample of ellipticals, whereas the spiral galaxies might be aligned perpendicular to the disks. Although the signal in both cases is consistent with 0, it nevertheless provides an interesting that deserves further study.

## 4 Outlook

The results presented in the previous two sections provide a crude picture of what weak lensing studies of galaxy halos can accomplish with current data sets. For galaxy-galaxy lensing studies both the RCS and SDSS data sets provide the most accurate results, with SDSS having the advantage of a larger number of galaxies with (photometric) redshift information. Even though these are early results (the galaxy-galaxy lensing was first detected less than a decade ago), already we can place interesting constraints on the properties of dark matter halos and the stellar contents of galaxies.

Much larger surveys have started. For instance, the second generation RCS aims to image almost  $850 \text{ deg}^2$  in  $g', r', z'$ . These data provide more than an order of magnitude improvement over the results discussed in these proceedings. The Kilo Degree Survey (KIDS) will start observations soon using the VLT Survey Telescope. This survey will image  $\sim 1500 \text{ deg}^2$  (to a depth similar to that of RCS2) in five filters, thus adding photometric redshift information for most of the lenses. The Canada-France-Hawaii-Telescope Legacy Survey will also provide important measurement of the lensing signal induced by galaxies. It is much deeper than RCS2 or KIDS, but will survey a smaller area of  $\sim 170 \text{ deg}^2$ , with cosmic shear measurements as the primary science driver. Nevertheless its signal-to-noise ratio of the measurements will be comparable to the RCS2, but it will have the advantage of accurate photometric redshift information from the 5 color photometry. Thanks to its added depth, it is also well suited to study the evolution of galaxy properties. Dedicated survey telescopes such as PanSTARRS or the LSST will image large portions of the sky, thus increasing survey area by another order of magnitude to a significant fraction of the sky.

One of the most interesting results from these projects will be a definite measurement of the average shape of dark matter halos. We can expect much progress on this front in the next few years. Although there is much reason for optimism, we also need to be somewhat cautious: the accuracy of the measurements is increasing rapidly, but it is not clear to what extent the interpretation of the results can keep up. The early results, presented here, have statistical errors that are larger than the typical model uncertainty. However, as measurement errors become significantly smaller, it becomes much more difficult to interpret the measurements: some more subtle effects arising from neighbouring galaxies or satellite galaxies can no longer be ignored. Instead, it will become necessary to compare the lensing measurements (i.e., the galaxy-mass cross-correlation function as a function of galaxy properties) to results of simulations directly. These future studies will provide unique constraints on models of galaxy formation as they provide measures of the role dark matter plays in galaxy formation.

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